AutoReaGas - A CFD-TOOL FOR GAS EXPLOSION HAZARD ANALYSIS

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1. INTRODUCTION

Gas explosions constitute a major hazard for offshore gas and oil producing installations. A gas explosion is the consequence of an accidental release of a flammable gas, the mixing with air and a subsequent ignition. Under appropriate boundary conditions the resulting flame propagation process may develop explosive combustion and damaging blast loadings. In spaces containing a lot of equipment, this is a particular problem and a small quantity of fuel may be sufficient to give rise to the development of high explosion overpressures. If such overpressures are not anticipated in the design they may have fatal consequences for both crew and rig.

The hazard of gas explosions offshore was demonstrated by the incident with the Piper Alpha rig in 1988 (Petrie[14]). A small-scale gas explosion caused the failure of vital control and communication functions on board. In consequence of this, the incident escalated to unforeseen circumstances leading to the total loss of the rig and the death of 167 people.

However, gas explosion effects can be controlled by a proper design of the installation. Modern offshore installations consist of a number of separate modules of limited size. Present understanding of the phenomena indicates that the module shape, the positioning of the equipment inside the module and the positioning and the size of vents largely affect the

development of an internal gas explosion.
So far, simple venting guidelines (e.g. Cubbage and Simmonds[9]; Bradley and Mitcheson[4,5]) are widely used to assess the consequences of possible gas explosions on board of offshore installations. Venting guidelines are empirical correlations based on experimental data. Most of the experimental data have been obtained in small-scale tests using near cubical, empty vessels. These guidelines, however, do not allow application beyond the experimental conditions they were derived from. Application to larger volumes of more complex geometries which contain many objects may lead to substantial underestimation of effects. For the design of adequate gas explosion control provisions in the offshore, more sophisticated methods are essential.

AutoReaGas is a software package capable of userfriendly, interactive, 3-D numerical simulation of any aspect of gas explosion phenomena. AutoReaGas contains both a gas explosion simulator and a blast simulator, each tailored to specific problem features.
After a general description of the phenomena and how they are modelled, in this paper the software is demonstrated in a practical offshore case study.

2. PHENOMENA

2.1 Gas Explosion

In a gas explosion a flammable gas mixture is consumed by a combustion process which propagates through the mixture in the form of a flame front. The flame front is the interface between cold reactants and hot combustion products. Because combustion products are of high temperature, the cold flammable medium expands strongly on combustion. The expansion induces a flow field whose structure is fully determined by the nature of its rigid boundaries. In this flow field the combustion process is carried along. The rate of combustion is strongly affected by the flow structure (velocity gradients and turbulence) met. Flow velocity gradients stretch the flame front, enlarge its interface and increase the effective combustion rate. Low intensity turbulence wrinkles the flame front with a similar effect on the combustion rate. Higher combustion rates intensify the expansion. Higher flow velocities go hand in hand with more intense turbulence levels. Higher turbulence levels speed up the combustion, etc. etc....... In other words: under the appropriate (turbulence generative) boundary conditions, a positive feedback mechanism is triggered by which a gas explosion develops exponentially both in speed and overpressure.

2.2 Blast

During the explosion process, the rapidly expanding combustion products do work on the surrounding medium. In this way, the chemical energy (heat of combustion) of the flammable mixture is partly converted into mechanical energy (expansion). Such a process is characterized by a thermodynamic efficiency with a maximum of approximately 40%. The mechanical energy is transmitted from the explosion into the surrounding atmosphere in the form of a blast wave. Such a blast wave may do damage on structures a large distance from the explosion.

An object struck by a blast wave experiences a blast loading which is a combination of two effects. On the one hand, a blast wave is experienced as a transient change in the static overpressure (a pressure wave) and on the other hand as a transient change in the medium velocity (a gust of wind). The pressure wave character induces a static pressure distribution while the medium velocity wave induces a fluid dynamic drag force on an object struck.

3. MODELLING

3.1 Gas Explosion

As outlined in Section 2, the essence of a gas explosion consists of the interaction of a premixed combustion process with its self-induced expansion flow field. The development of this process is predominantly controlled by the turbulence induced in the flow field by the boundary conditions. Modelling of a gas explosion requires careful modelling of all aspects of this complicated process. The model underlying the AutoReaGas gas explosion simulator can be characterized as follows:

- The gas dynamics is modelled as a perfect gas which expands as a consequence of energy addition. This is mathematically formulated in conservation equations for mass, momentum and energy, i.e.: the Navier-Stokes equations.
- The energy addition is supplied by combustion which is modelled as a one step conversion process of flammable mixture into combustion products. This is formulated in conservation equations for the fuel mass fraction and the composition. The combustion rate is a source term in the fuel mass fraction conservation equation.
- Turbulence is modelled by a two parameter model (k-ε) which consists of conservation equations for the turbulence kinetic energy k and its dissipation rate ε (Launder and Spalding[11]).

- Turbulent combustion is modelled by an expression which relates the combustion rate to turbulence. Several options are available varying from theoretical relations such as the Eddy Break Up model (Spalding[15]) and the Eddy Dissipation model (Magnussen and Hjertager[12] and Hjertager et al.[10]) up to experimental correlations between turbulence and combustion (Bray[6]). Because the applied cell size is often too large to fully resolve a turbulent combustion zone, the combustion rate is corrected.
- The initial stage of combustion upon ignition is modelled by a process of laminar flame propagation whose speed is controlled on the basis of experimental data.
- Objects too small to be represented by solid boundaries in the computational mesh, are modelled by a subgrid representation. The presence of a subgrid object is modelled by the specification of appropriate flow conditions: i.e.: a fluid dynamic drag and a source of turbulence.
- Numerical solution of the set of equations is accomplished by means of the "power law" scheme applied within a finite volume approach (Patankar[13]).

3.2 Blast

As long as objects with large cross-flow dimensions are considered, the interaction with gas explosion blast is predominantly governed by the pressure wave character of the blast. The drag component can be neglected. The pressure wave character of blast flow fields can be accurately represented by the assumption of inviscid flow. Often, blast flow fields are characterized by the presence of gas dynamic discontinuities such as shocks. Modelling of blast-object interaction requires careful description of such phenomena. Therefore, the blast simulator in AutoReaGas models blast-object interaction as follows:

- The gas dynamics is modelled as inviscid compressible flow of a perfect gaseous fluid which can be formulated in the conservation equations for mass, momentum and energy for inviscid flow, i.e. the Euler-equations.
- Description of shock phenomena requires a sophisticated numerical technique tailored to proper representation of steep gradients. To this end, the blast simulator utilizes Flux-Corrected Transport (FCT) (Boris and Book[2] and Boris[3]). FCT makes an optimized use of numerical diffusion so that steep gradients present in shocks are retained. Numerical diffusion is added only where it is required for numerical stability.

4. ANALYSIS OF A GAS EXPLOSION ON AN OFFSHORE PLATFORM

4.1 Problem

Modern offshore installations are characterized by a modular structure. The various aspects of the oil and gas production process take place in different areas separated by fire/blast resistant walls. The intention is to keep the consequences of a possible incident within bounds - the module.

In case of a gas explosion the internal overpressure can be controlled by venting any expanding gases. Therefore, modern modules are constructed so that they are as open as possible. Outer walls often consist of light-weight windcladding or windscreens which are attached to the main structure in such a way that they may easily fail and are blown off at a low internal overpressure.

A vented gas explosion gives rise to an external explosion. As soon as the combustion process in the module is initiated, the flammable mixture inside the module starts venting in the form of a turbulent flammable jet. This jet explodes when it is ignited at the time the combusting gas mixture vents. The resulting blast may do damage to, for instance, nearby equipment and structures.

A vented gas explosion is the subject in the present analysis carried out with AutoReaGas. Figure 1 shows a highly simplified, made up representation of an offshore production platform. The platform consists of a main deck and a cellar deck. The main deck consists of several modules. One of these modules is almost completely built in. The only possibility for venting for this module is the space on deck between the modules and the living quarters. At this side the module is left completely open as a vent. The consequences of a gas explosion in this module are analyzed by applying the AutoReaGas software.

This exercise addresses the following questions. What is the overpressure developed by a gas explosion in the module? What is the blast loading of a 3 m diameter, 8 m long vessel and a 0.3 m diameter tube present on deck in front of the vent opening and what are blast overpressures at the wall of the living quarters?

4.2 Analysis

A computational domain is specified. The domain, consisting of 40*20*20 cells of 1 m^3 size, covers the module as well as the space between module and living quarters. Within this domain, the software allows the specification of the physical layout of any system of rigid boundaries e.g. boxes, beams, vessels and tubes by means of a CAD-like interface.

Figure 2 represents an AutoReaGas configuration of the domain showing only the larger pieces of equipment. The module (left) is filled with a number of horizontal and vertical vessels, interconnected with a lot of piping and appendages. A 3 m diameter, 8 m long vessel (A) as well as a 0.3 m diameter tube are defined in the space on deck between module and living quarters (right).

The specified configuration of objects in the domain is automatically converted by the software into the proper input for the explosion simulator. Large objects are represented by rigid boundaries while the presence of small objects is modelled by the subgrid formulation. The software allows the specification of any distribution of fuel in the domain which can be ignited in any desired location. However, to approach worst case conditions in this problem, the module is assumed to be filled with a stoichiometric propane-air mixture and ignited in the centre of the back wall.

The AutoReaGas software allows fully interactive simulation, showing the distributions of any specified process parameter on the screen, any wanted number of time steps again. Figure 3 shows a compilation of such a series of pictures. The pictures show the temperature field in both a horizontal and vertical cross-section at a number of consecutive points of time. The temperature is visualized by means of a suggestive colour gradation. The timing of the pictures indicates how the flame propagation process develops. After a slow laminar start, it speeds up under the influence of the equipment in the module. The combustion process vents in the form of a mushroom-like shaped flame front, which is fully in line with experimental observations (Catlin[7] and Bimson et al.[1]).

During the simulation, process parameters can be monitored throughout the domain. Figure 4 represents the overpressure traces recorded inside the module in the gauges 1 (ignition point) and 2 (vent opening). The traces show the characteristic behaviour of a gas explosion: a relatively long initial phase of slow development and low overpressure progressing into a more violent development characterized by a sudden pressure pulse. A maximum internal overpressure of approximately 70 kPa is observed at the back wall of the module.

The Figure 5 represents five overpressure traces (3 - 7) recorded at the living quarters's wall in front of vent opening (Figure 2). All traces are more or less similar showing a double-peak shape with a maximum of approximately 40 kPa.

The blast loading of the 3 m diameter vessel on deck is monitored by recording the pressure differential between the front and back area of the vessel. This pressure differential is represented in Figure 6. Multiplication of this pressure differential with the cross-sectional area of the vessel immediately results in the horizontal force induced by the vent flow.

The blast loading of the 0.3 m diameter tube is recorded by monitoring both the density and gas velocity components in three different gauges in the row of cells in which the tube is specified as a subgrid object. The force on the tube per meter length is calculated from these parameters assuming a drag coefficient equal to 1. The drag force on the tube per meter length as a function of time is represented in Figure 7. The double-peak shape, amplitude and duration of the tube load are in line with experimental observations (Catlin[8]).

The double-peak shape of the various loading traces seems to be characteristic and can be explained considering the process parameters in more detail. Stagnation pressures are proportional to both the density and the square of the flow velocity. Initially, stagnation pressures are the result of relatively low-velocity/high-density flow, i.e. the blast from the internal and external explosion. At the instant the gauges are reached by low-density combustion products, stagnation pressures drop. Stagnation pressures rise again in the growing burned gas vent velocities. Gas vent velocities tend to increase strongly at the instant combustion products start venting.

5. CONCLUSION

AutoReaGas is a CFD-tool for analysis of gas explosion problems. AutoReaGas consists of a gas explosion simulator and a blast simulator, placed in a user friendly environment. Several possibilities of the software were demonstrated in a practical case study. Problems can be defined in a userfriendly CAD-like environment. Computational results indicate that the software is capable of realistic simulation of (vented) gas explosions. The exercise in this paper demonstrated the possibility of detailed computation of the blast loading of objects specified in the computational domain.

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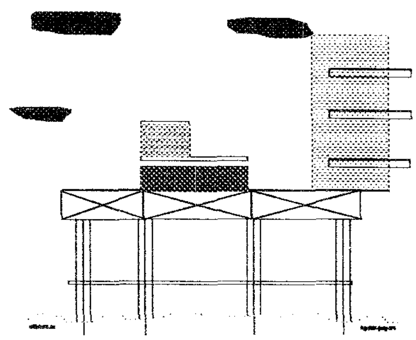


Figure 1 Offshore oil and gas production platform

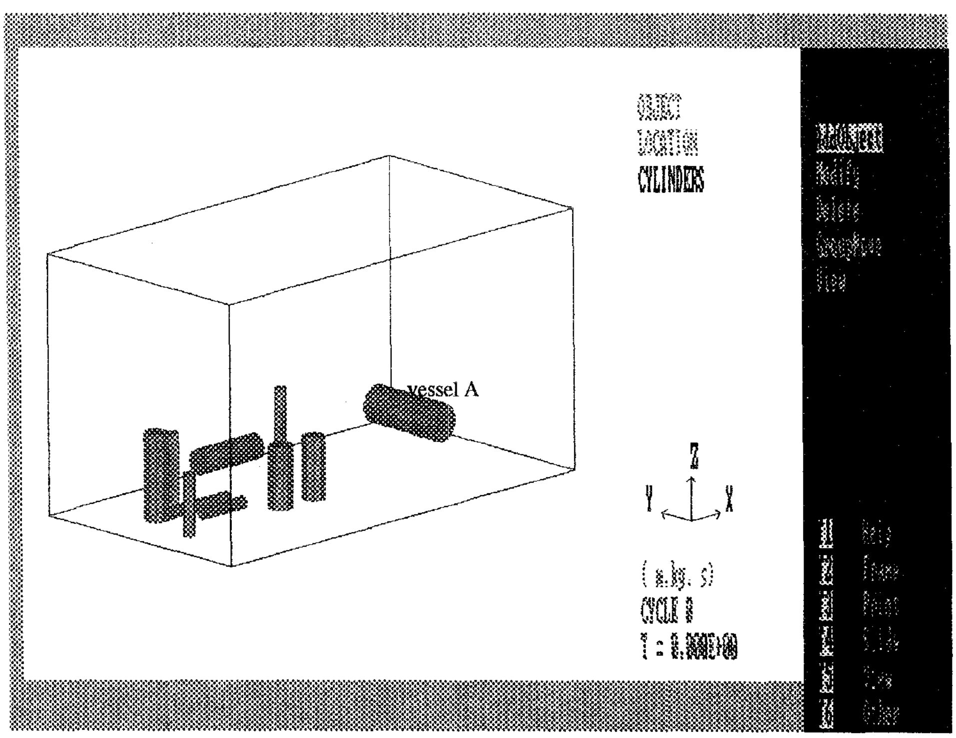


Figure 2 AutoReaGas process equipments representation.

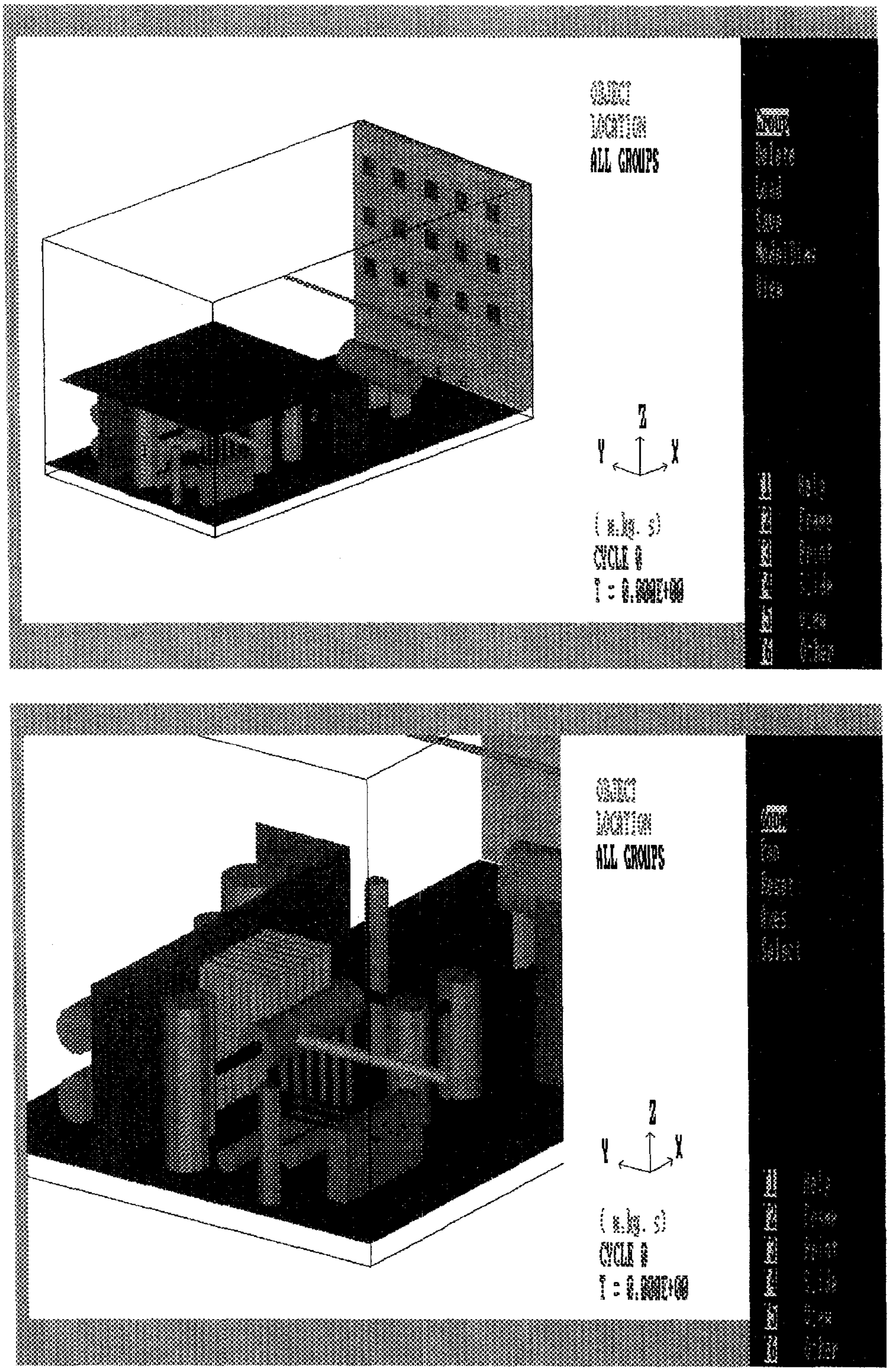


Figure 2 AutoReaGas process equipments representation (cont).

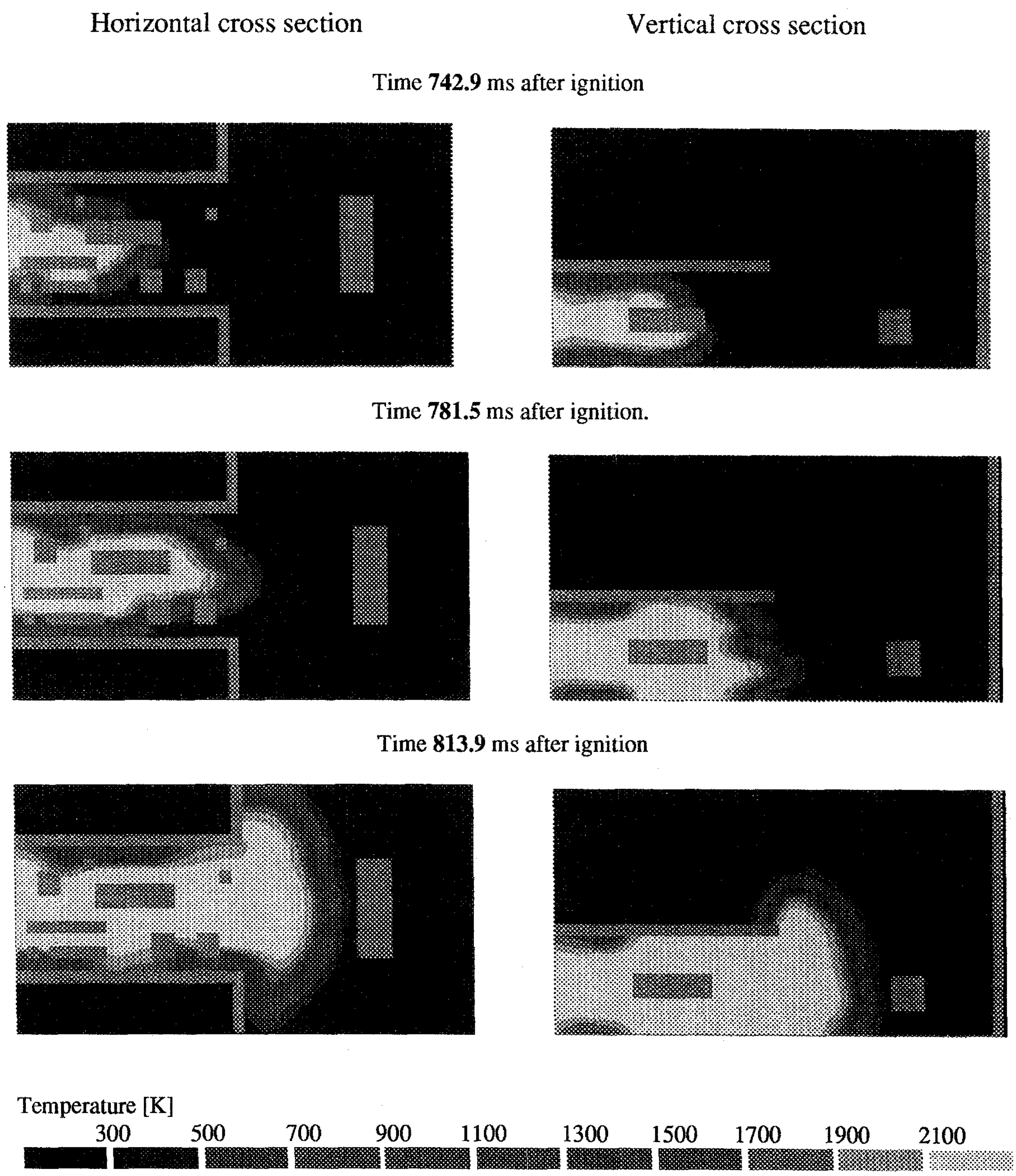


Figure 3 Compilation of AutoReaGas process monitoring.

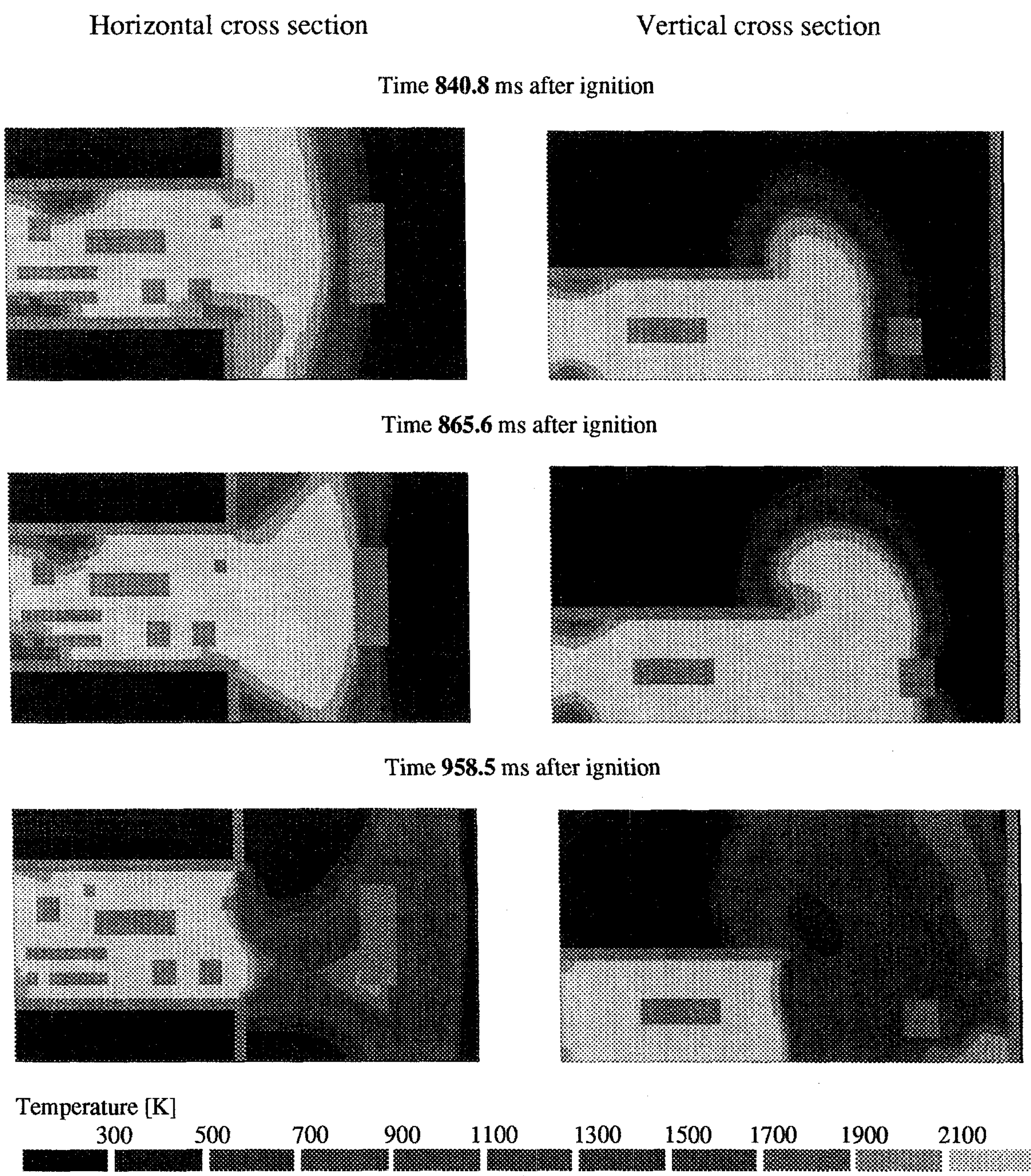


Figure 3 Compilation of AutoReaGas process monitoring (cont).

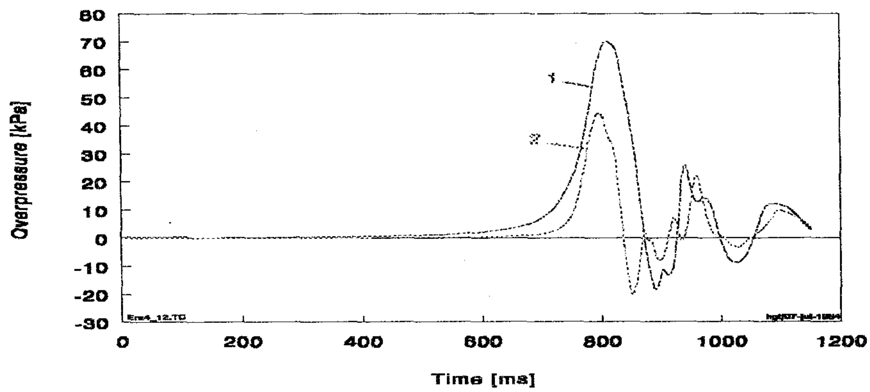
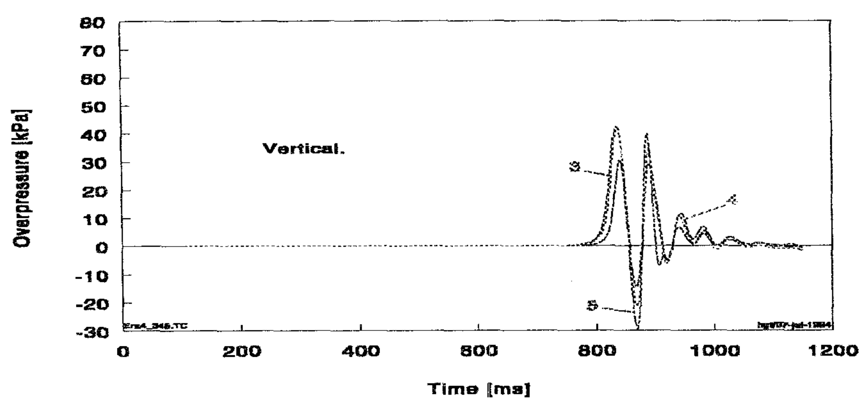


Figure 4 Overpressure-time traces recorded at gauges 1 and 2 inside the module



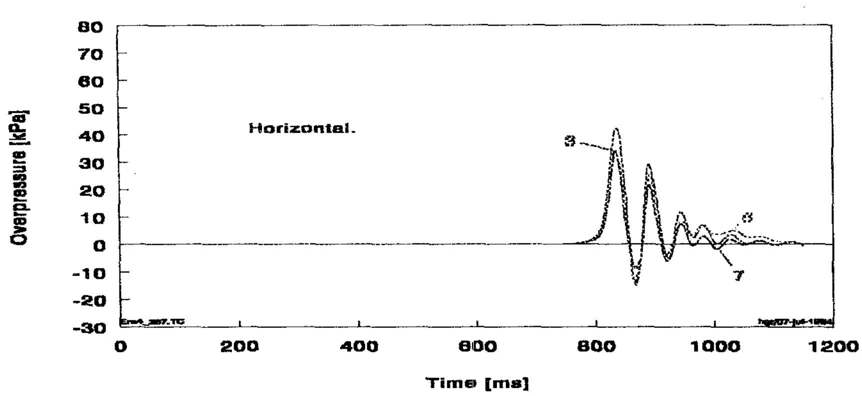


Figure 5 Overpressure-time traces recorded at gauges 3 up to 7 located at the wall of the living quarters.

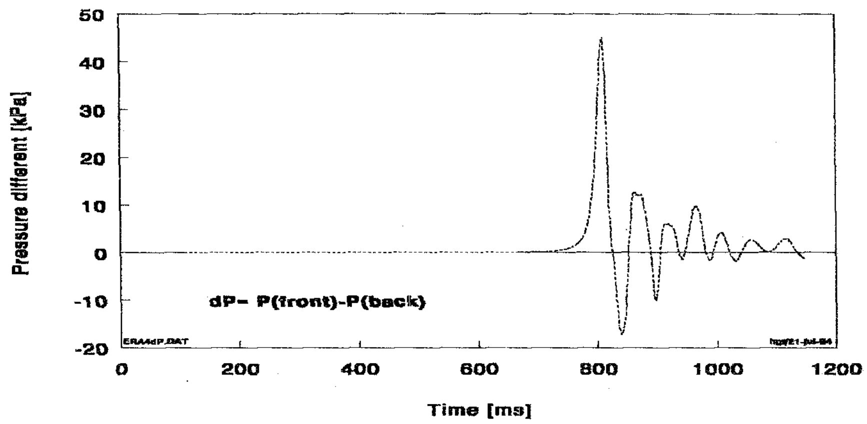


Figure 6 Pressure differential between front and back area of vessel A on deck.

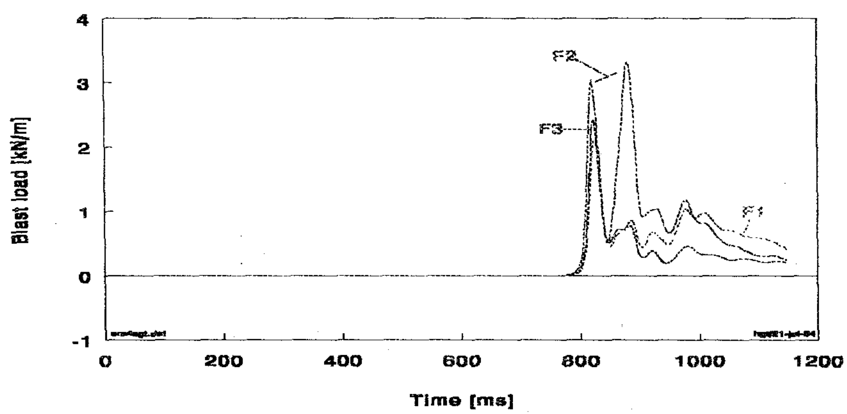


Figure 7 Blast loading at three gauges along a pipe above vessel A.